

Update on Heavy-Duty Low NO_x Demonstration Programs at SwRI

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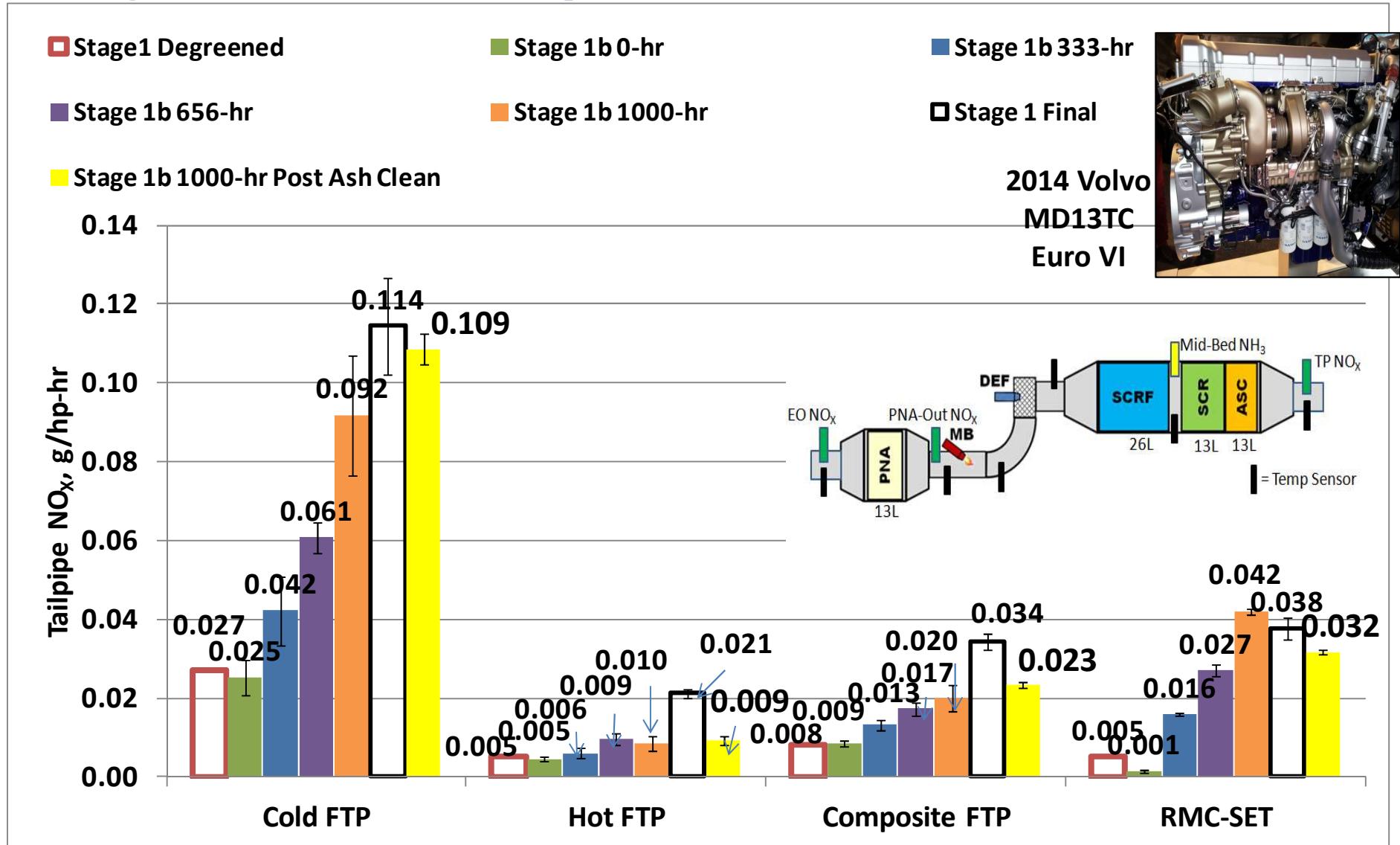
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CARB Low NO_x Programs at SwRI

- **Stage I** – Evaluating Technologies and Methods to Lower Nitrogen Oxide Emissions from Heavy-Duty Vehicles (2014-2017) - **COMPLETE**
 - Initial Technology Evaluation – Diesel and CNG
 - Primary focus on Regulatory Cycles
- **Stage Ib** – Repeat Aging and Evaluation of Stage I Hardware (2018-2019) - **REPORTING**
 - Answer questions from Stage 1 and provide robust parts for Stage 2
- **Stage 2** – Heavy-Duty Low Load Emission Control (2017-2019) - **REPORTING**
 - Expand previous technology evaluation to low-load and urban operating cycles
 - Evaluation of in-use testing metrics to evaluate emissions at low loads
- **Stage 3** – Further Evaluation and Development of Low NO_x Technologies on 2017 (non-Turbocompound) Engine Platform (2018-2020)
 - Focus on both Low Load (Real world) and Regulatory cycles
 - ***Stage 3b – Engine Hardware Technology Effort organized by SwRI to augment Stage 3***



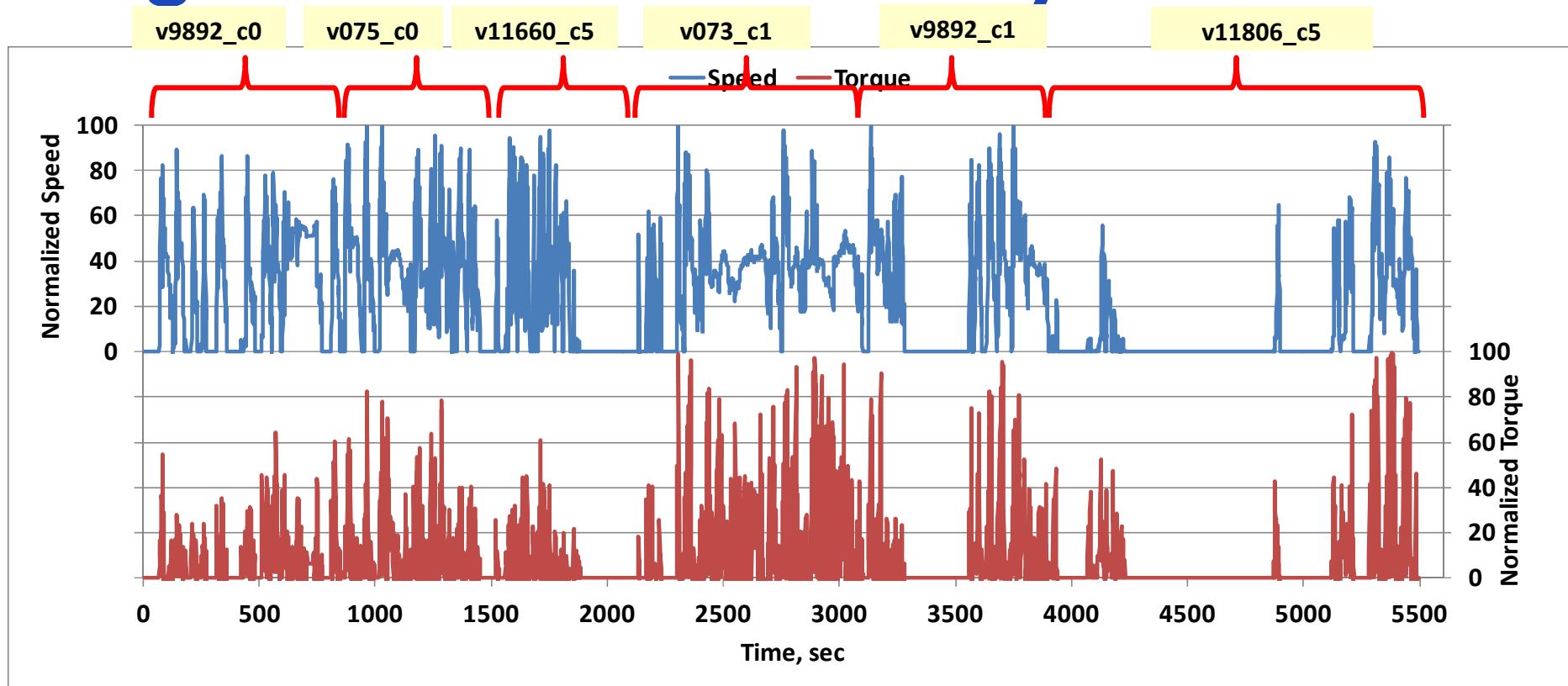
Stage 1b Results – Updated Data Set with FUL Tests



Note: UAF of +0.004 g/hp-hr is added to these to account
for infrequent regeneration impact

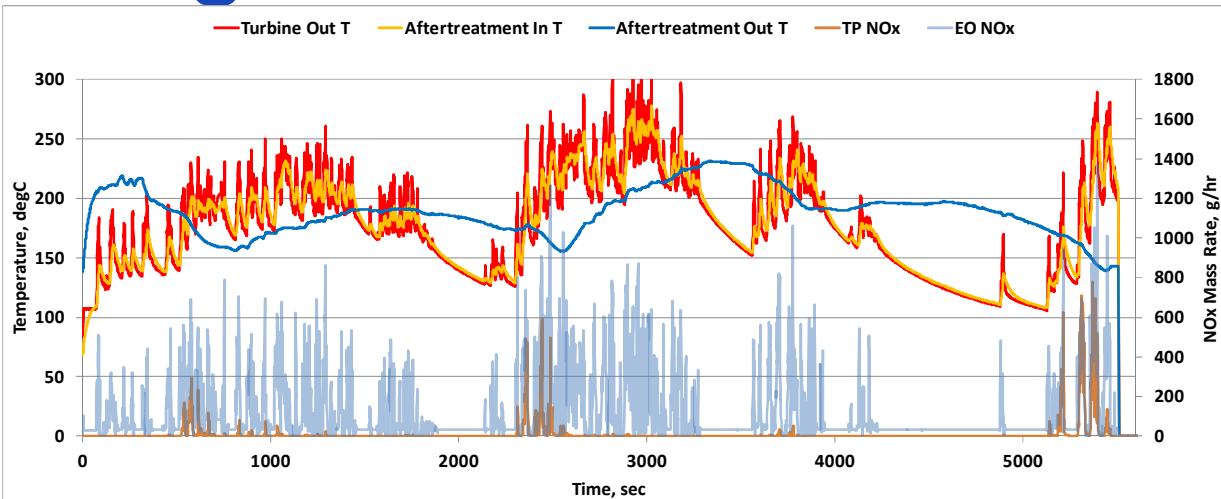
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Stage 2 - Final Low Load Cycle



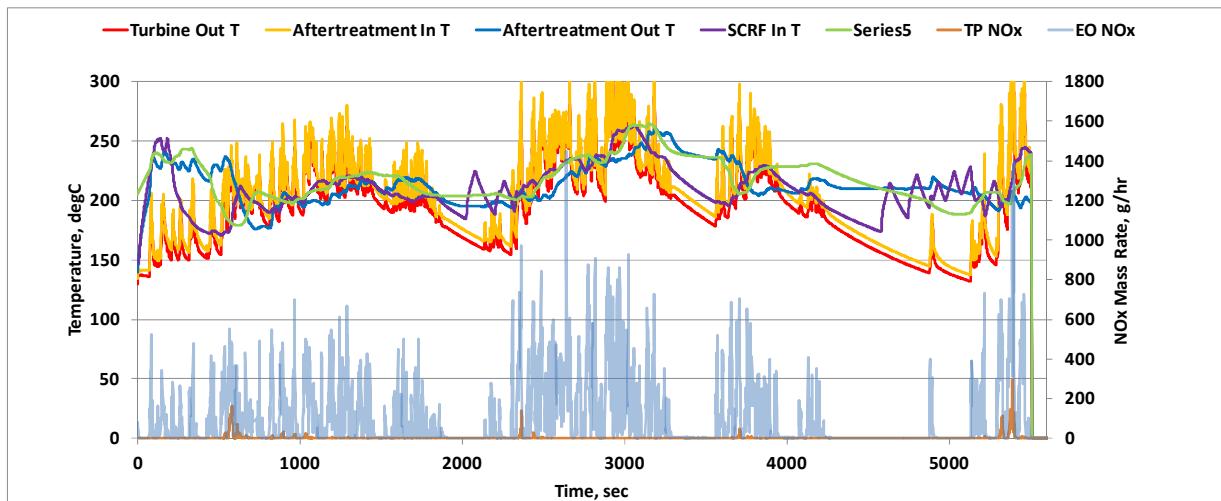
- Developed from real world vehicle operations at Low Load
- Average power generally 7-8% of engine max (with idle load)
- Run with accessory load at idle
 - HHD: 3.5kw, MHD: 2.5kw, LHD: 1.5kw (from EPA GEM defaults)
- TP NO_x Levels on Current Production engines – 0.35 to 1.5 g/hp-hr
 - average ~ 1 g/hp-hr

Stage 2 - LLC Performance on Stage 1 / 2 Engine



Stage 2 - Baseline EU 6 System

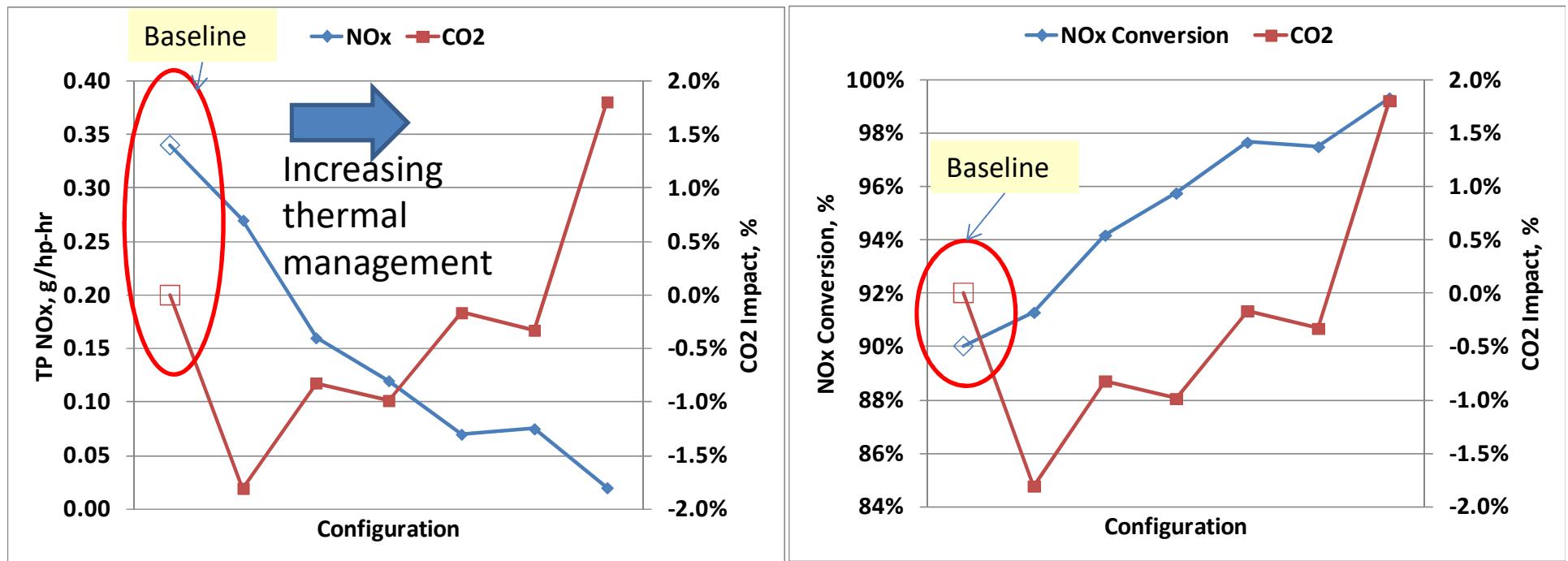
- Overall 90% conversion
- $\text{EO NO}_x = 3.4 \text{ g/hp-hr}$
- $\text{TP NO}_x = 0.34 \text{ g/hp-hr}$
- $\text{CO}_2 = 607 \text{ g/hp-hr}$



Stage 2 - Low NO_x Engine

- Overall 97.5% conversion
- $\text{EO NO}_x = 3.0 \text{ g/hp-hr}$
- $\text{TP NO}_x = 0.07 \text{ g/hp-hr}$
- $\text{CO}_2 = 608 \text{ g/hp-hr}$

Updated Stage 2 LLC Result Comparison



- Stage Ib Baseline MDI3TC EU6 - 90% conversion on LLC
- Without thermal management, 91% conversion and CO₂ is improved by 2% on LLC
- Highest level of thermal management shows 2% CO₂ penalty for 0.02 g/hp-hr NO_x on LLC
- “Optimized” thermal management at 0.07 g/hp-hr NO_x is fuel consumption neutral

Stage 3 Low NO_x Demonstration Program

- Examine potential for Low NO_x on a platform that is more representative of broader market in 2017+
 - Production 2017 Cummins X15
 - More representative of typical U.S. GHG approach
- Integrate both Regulatory and Low Load Cycles at the start
 - Program targets are 0.02 g/hp-hr on regulatory cycles and control on Low Load cycles

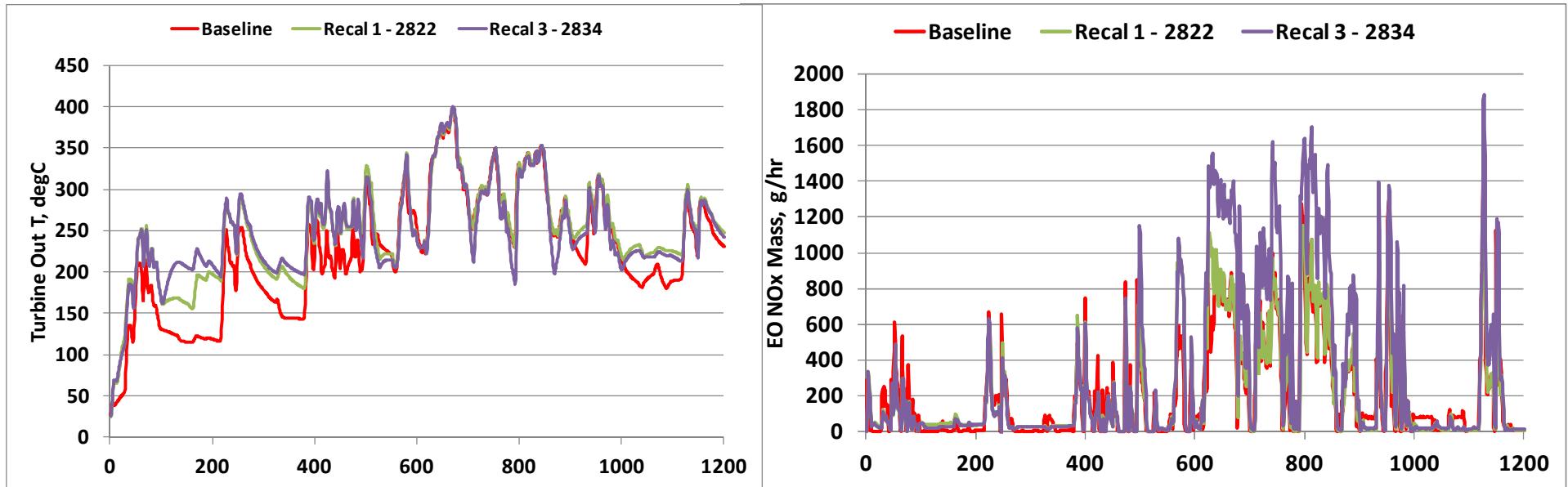


2017 Cummins X15

Production
Aftertreatment
(replaced for Low NO_x)



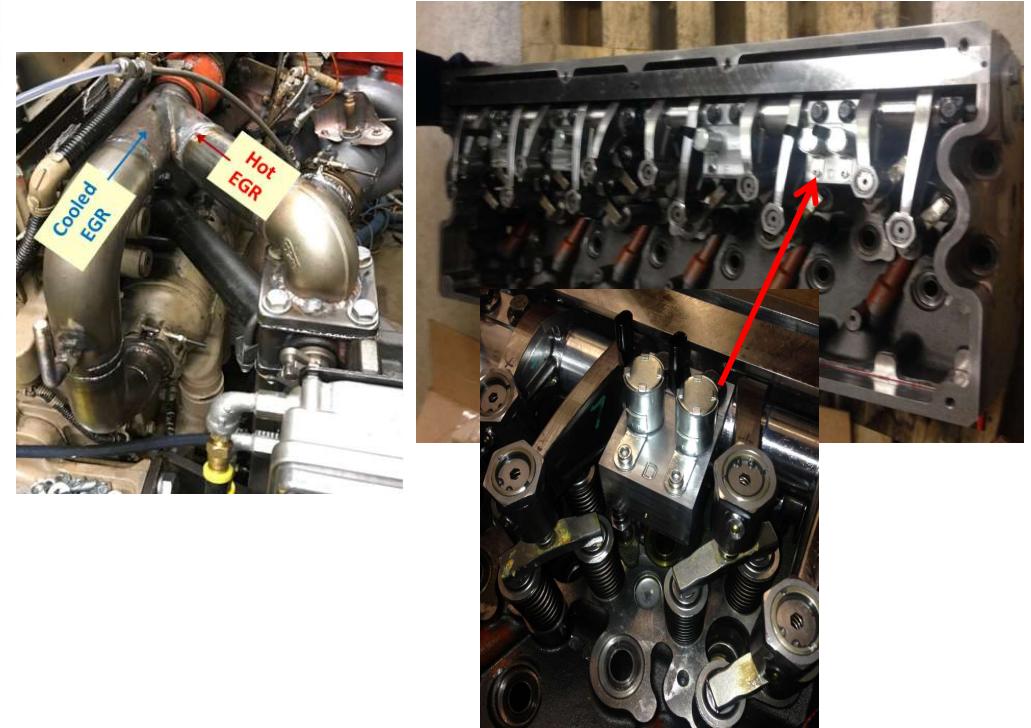
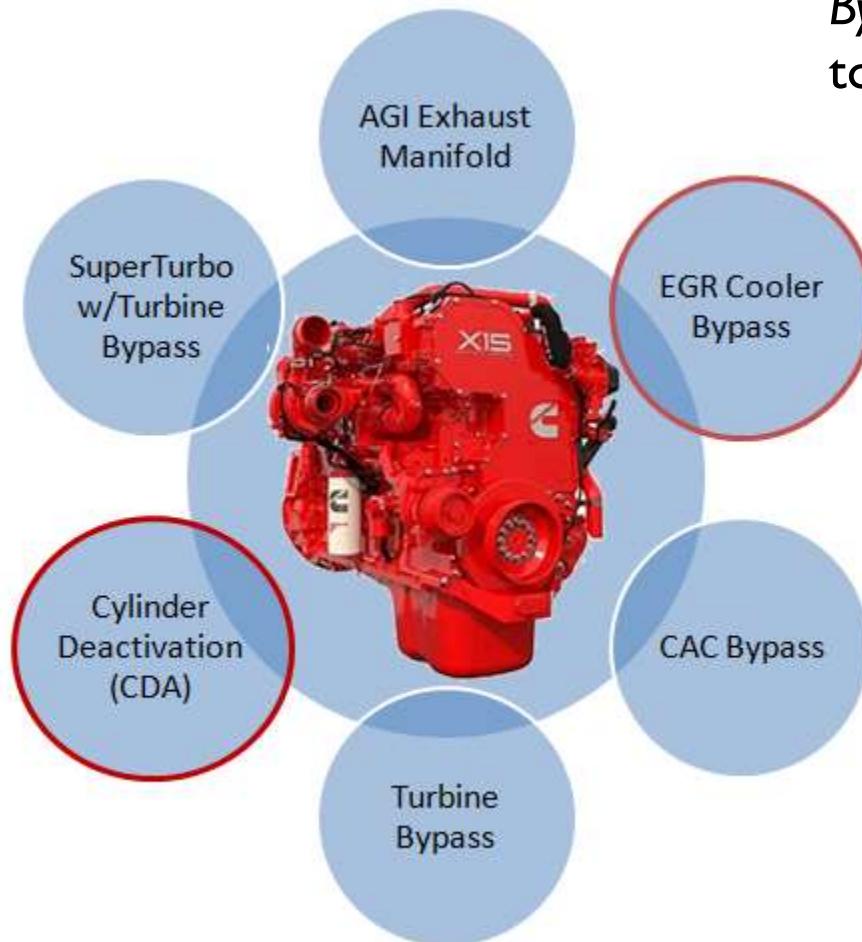
Stage 3 – Modified Engine Calibration (Cold FTP Example)



- 2017 Cummins X15 – stock engine hardware
- Modified Calibration Elements – Modified EGR, VGT, multiple injections, elevated idle, etc...
- Elevated T and Reduce EO NO_x early (some GHG cost)
- Higher EO NO_x later for (mitigate some of GHG cost)
- Note that Cold-FTP Recal 3 has +4% impact on CO₂ (+0.6% to Composite)

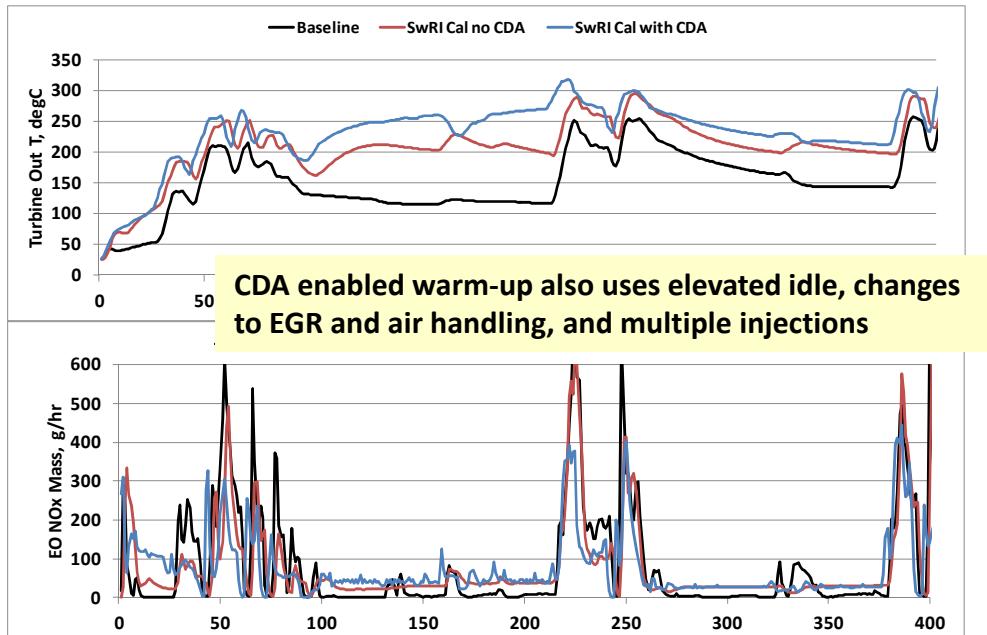
Stage 3b – Additional Engine Hardware Evaluated

- **Cylinder Deactivation (CDA)** and *EGR* Cooler Bypass selected as final choices to carry forward to Stage 3 demonstration
 - Hardware evaluations indicated sufficient value to justify hardware cost



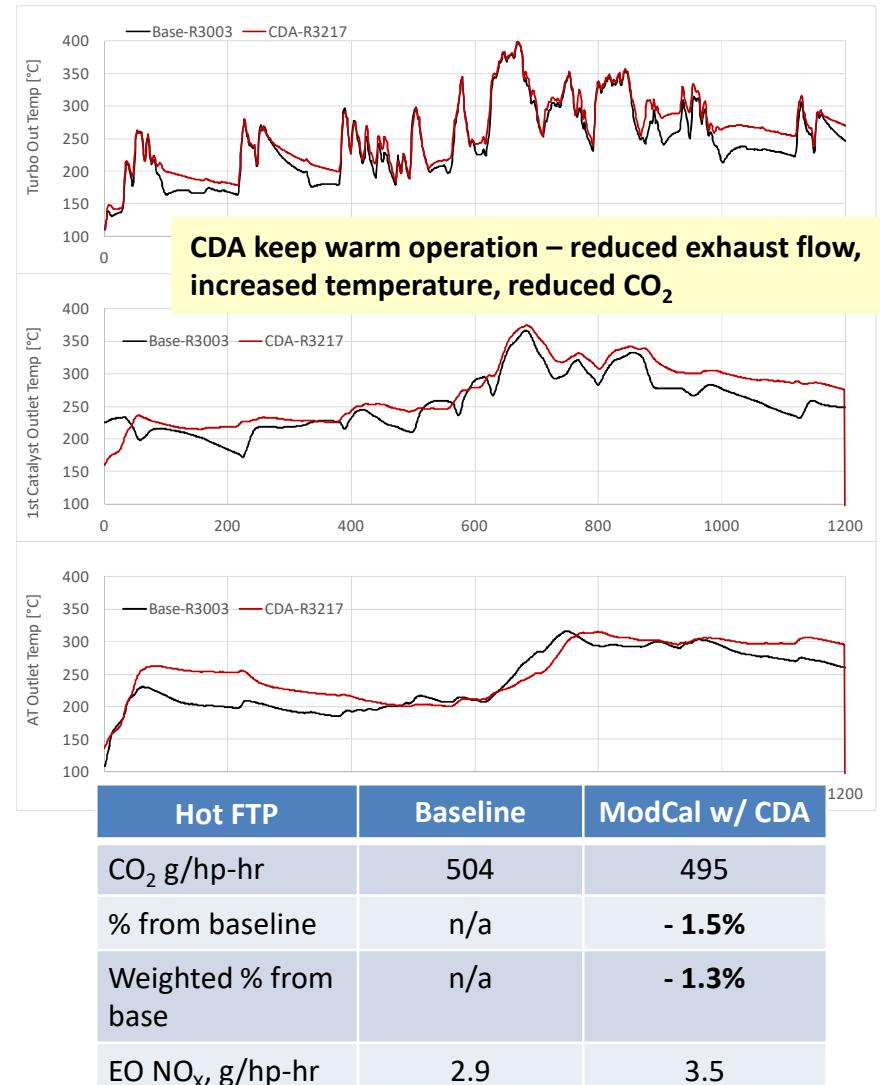
Stage 3 - Using CDA to Improve AT System Conditions and Fuel Consumption

Cold-Start FTP ("Get Hot")



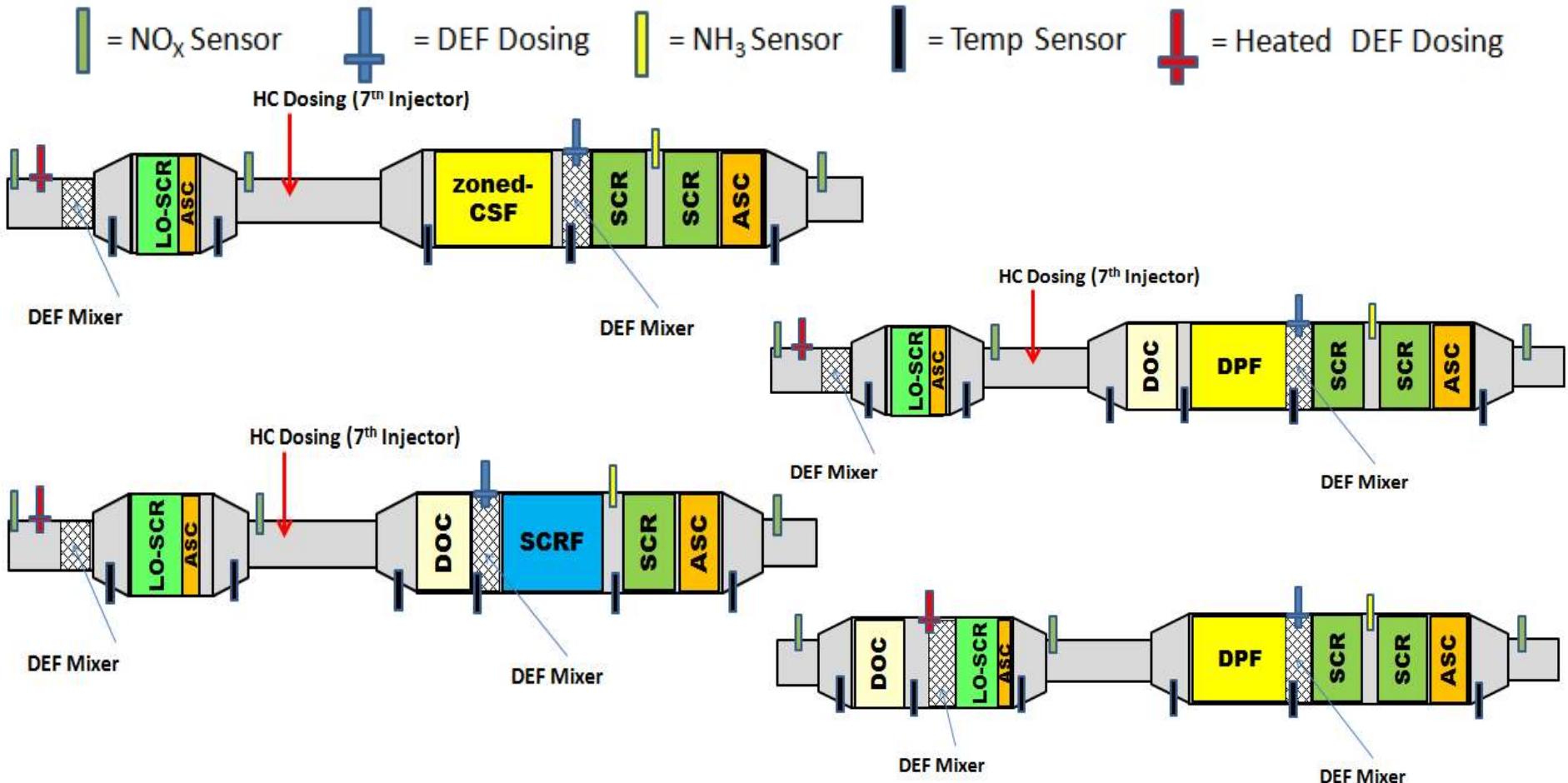
Cold FTP	Baseline	ModCal	ModCal w/ CDA
CO ₂ g/hp-hr	531	552	538
% from baseline	n/a	+ 4.0%	+ 1.3%
Weighted % from base	n/a	+ 0.5%	+ 0.2%
EO NO _x , g/hp-hr	2.0	3.2	3.0

Hot-Start FTP ("Stay Hot")



Stage 3 Aftertreatment – Configurations Examined

Integration and Evaluation Complete

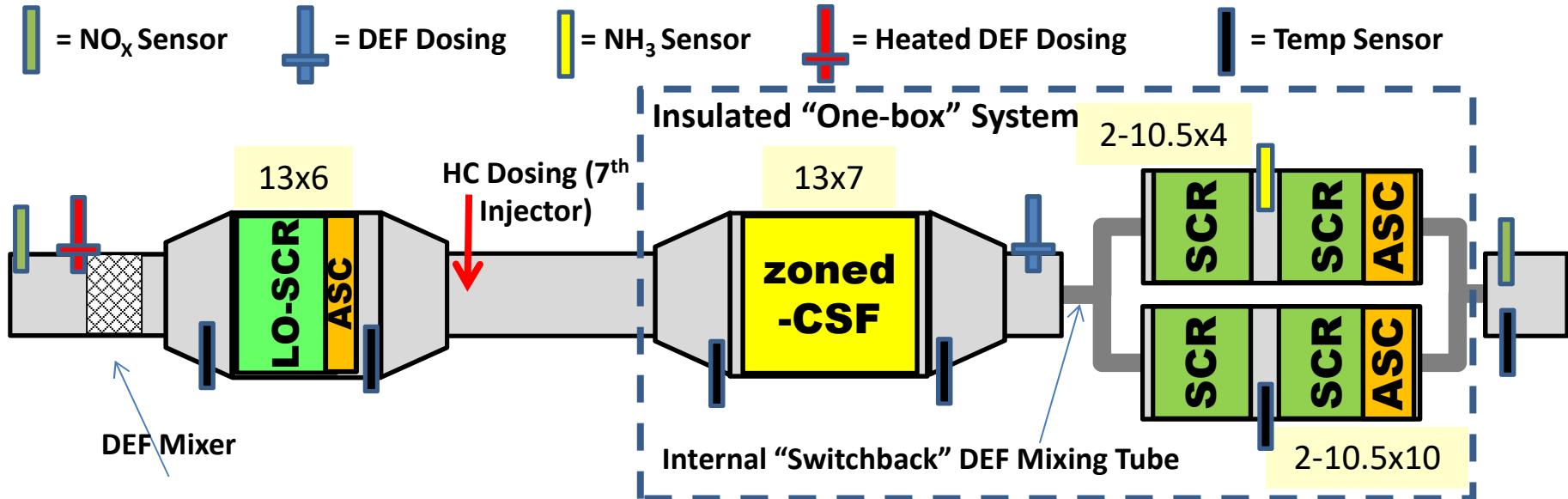


- Development Aged parts – hydrothermally aged to 435,000 miles FUL (Current Data)
- Final Aged parts – thermal and chemical aging to 435,000 miles FUL using DAAAC protocol (Final Demonstration) – 10X acceleration factor

Stage 3 - Updated System Comparisons

	Baseline	Config 2B	Config 1A
Cold FTP NO _x	0.27	0.043	0.054
Cold FTP CO ₂	531	542	545
Hot FTP NO _x	0.14	0.014	0.012
Hot FTP CO ₂	505	500	502
LLC NO _x	1.4	0.12 / 0.053	0.16 / 0.036
LLC CO ₂	624	593 / 609	614 / 633
Backpressure	24	36	25
RMC-SET NO _x	0.15	-	0.026 (no optimization at all and no upstream help)
RMC-SET CO ₂	454	- (but likely higher)	455

Stage 3 - Final Aftertreatment System Schematic (Hybrid of 2B + IA)



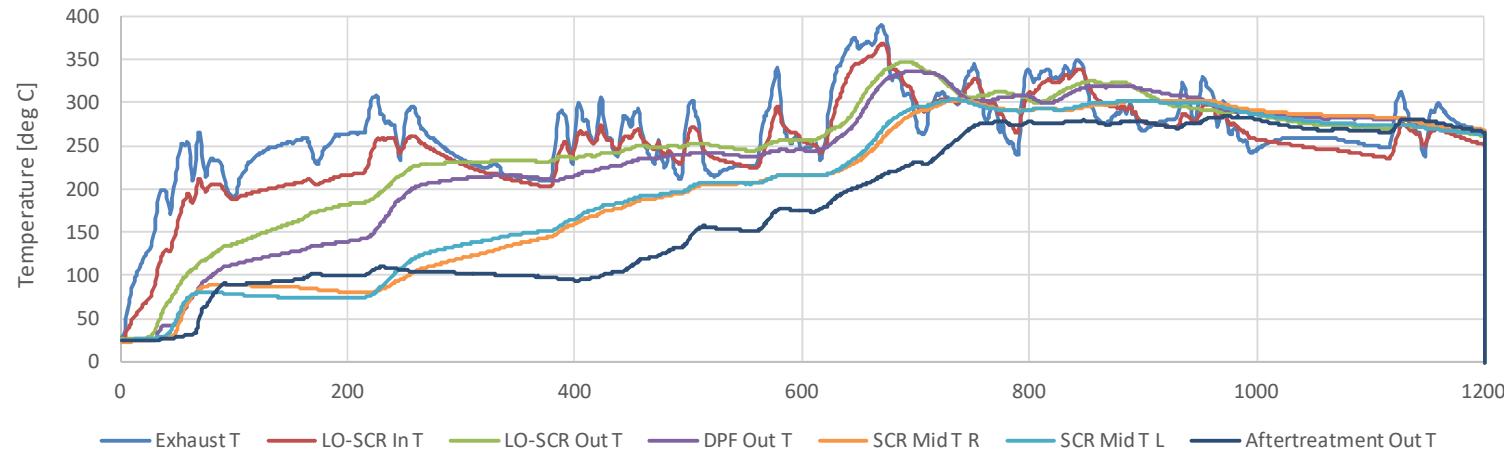
- Zone coated CSF for reduced thermal inertia upstream of dsSCR
- Need 7th injector to avoid HC exposure on LO-SCR
- Similar deSO_x questions for LO-SCR

LOSCR	13x6	400/4	with ASC zone coated
zonedCSF	13x7	300/7 HAC	DOC coating front CSF coating back
SCR	2-10.5x4	600	dual parallel paths
SCR-ASC	2-10.5x10	600	dual parallel paths, with ASC zone coated

Stage 3 - Cold FTP Performance – 2B+1A

Run 3388 - CFTP - ModCalR13AH7 - wCDA - Team 2B+1A - Model-based Dosing Rev 11

ANR + Rev 10 Storage Targets



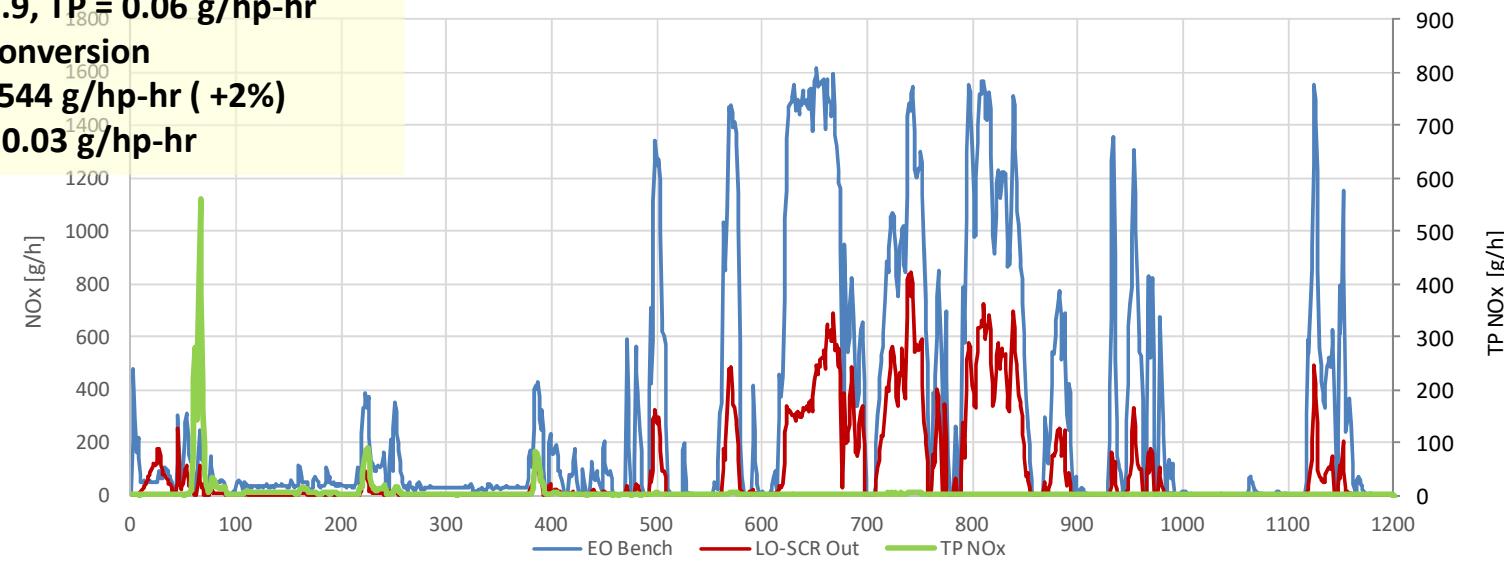
EO = 2.9, TP = 0.06 g/hp-hr

98% Conversion

CO₂ = 544 g/hp-hr (+2%)

N₂O = 0.03 g/hp-hr

Note TP
lower axis
(green trace)



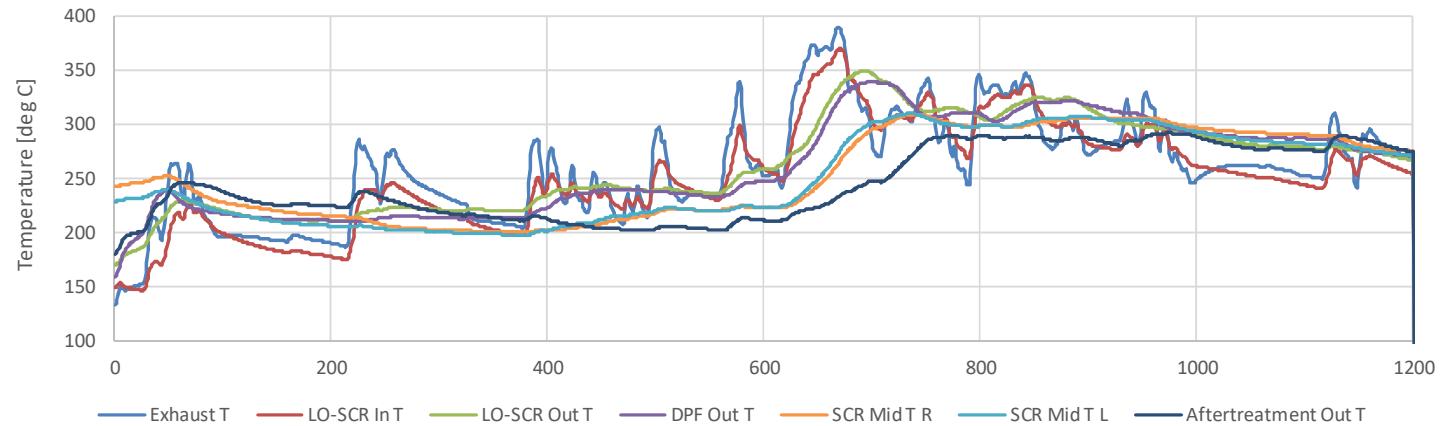
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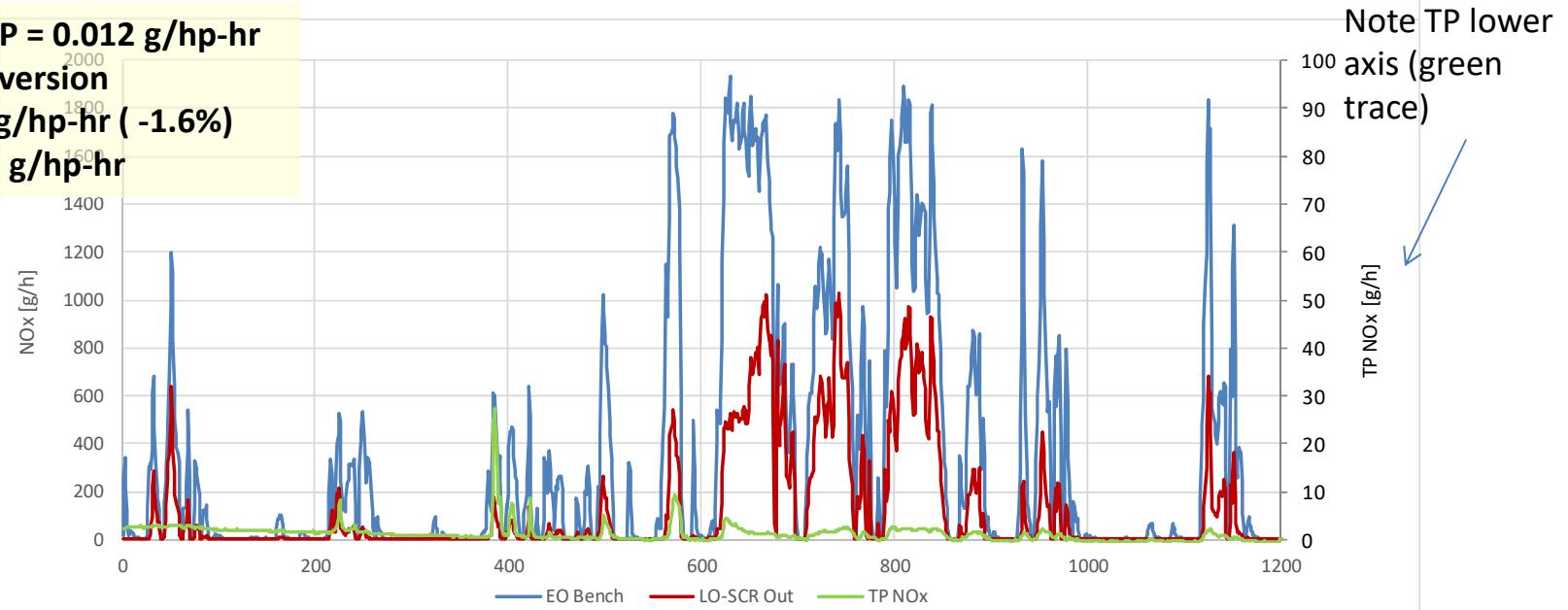
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Stage 3 - Hot FTP Performance – 2B+1A

Run 3395 - HFTP1 - BaseCalR13+8192 - wCDA - Team 2B+1A - Model-based Dosing Rev
11 ANR FF + Rev 11 Storage Targets



EO = 3.4, TP = 0.012 g/hp-hr
99.6% Conversion
CO₂ = 496 g/hp-hr (-1.6%)
N₂O = 0.07 g/hp-hr

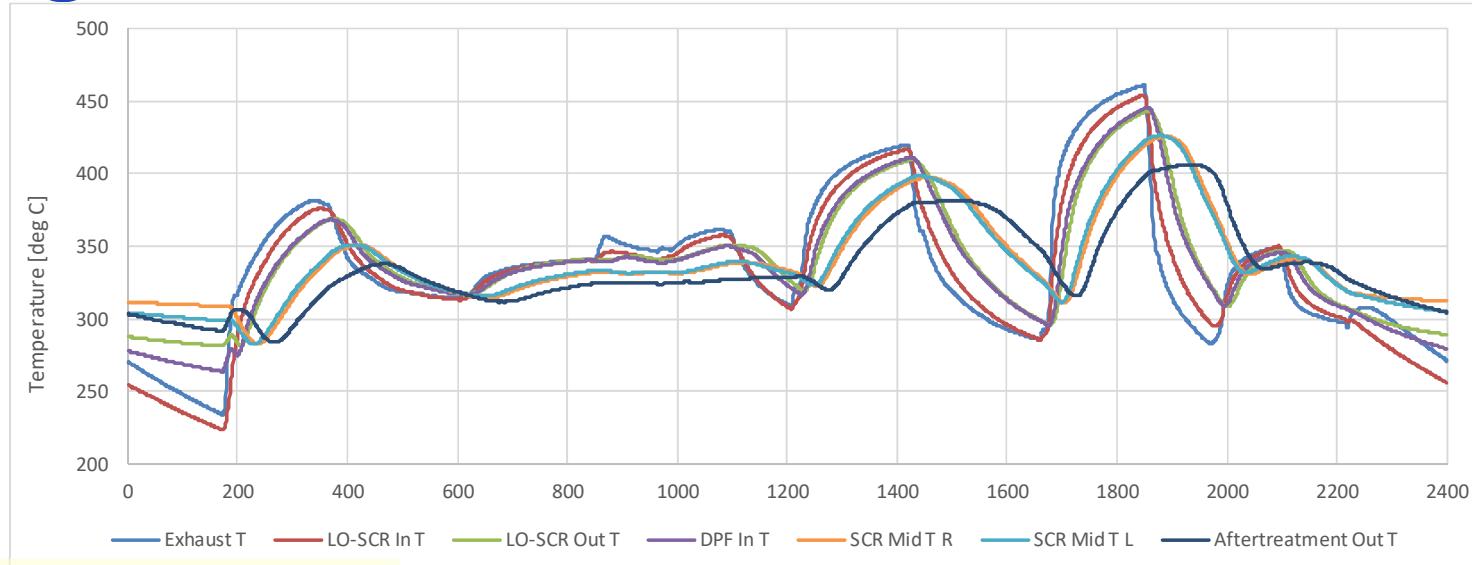


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Stage 3 - RMC-SET Performance – 2B+IA

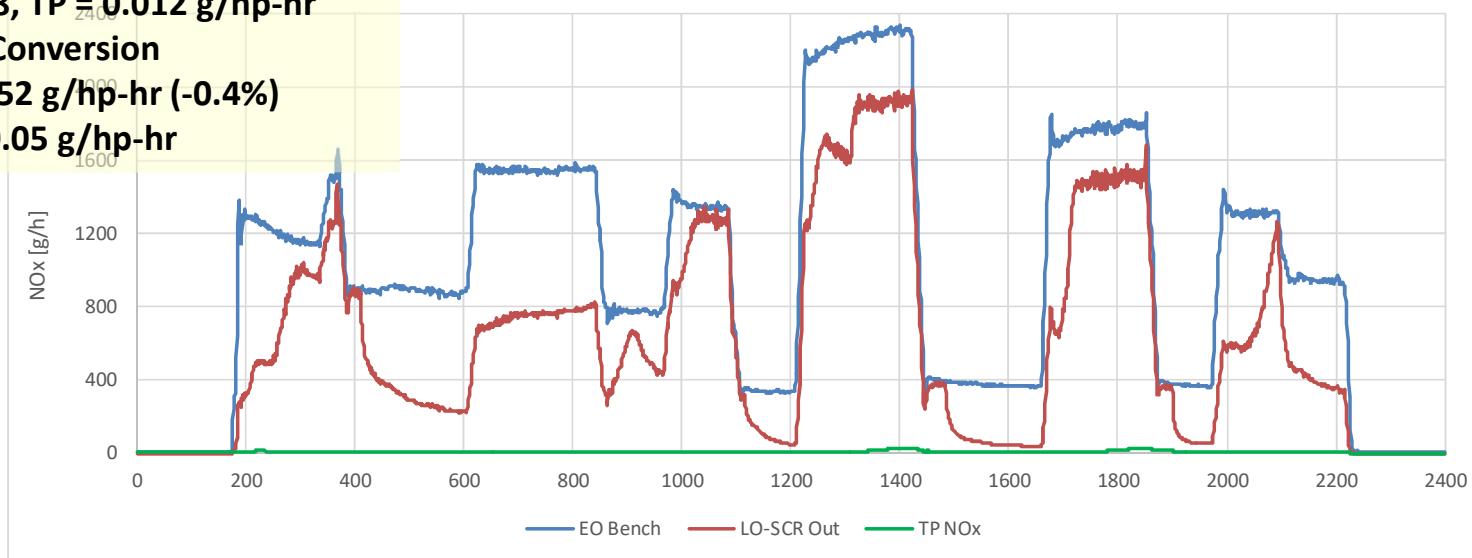


EO = 3.8, TP = 0.012 g/hp-hr

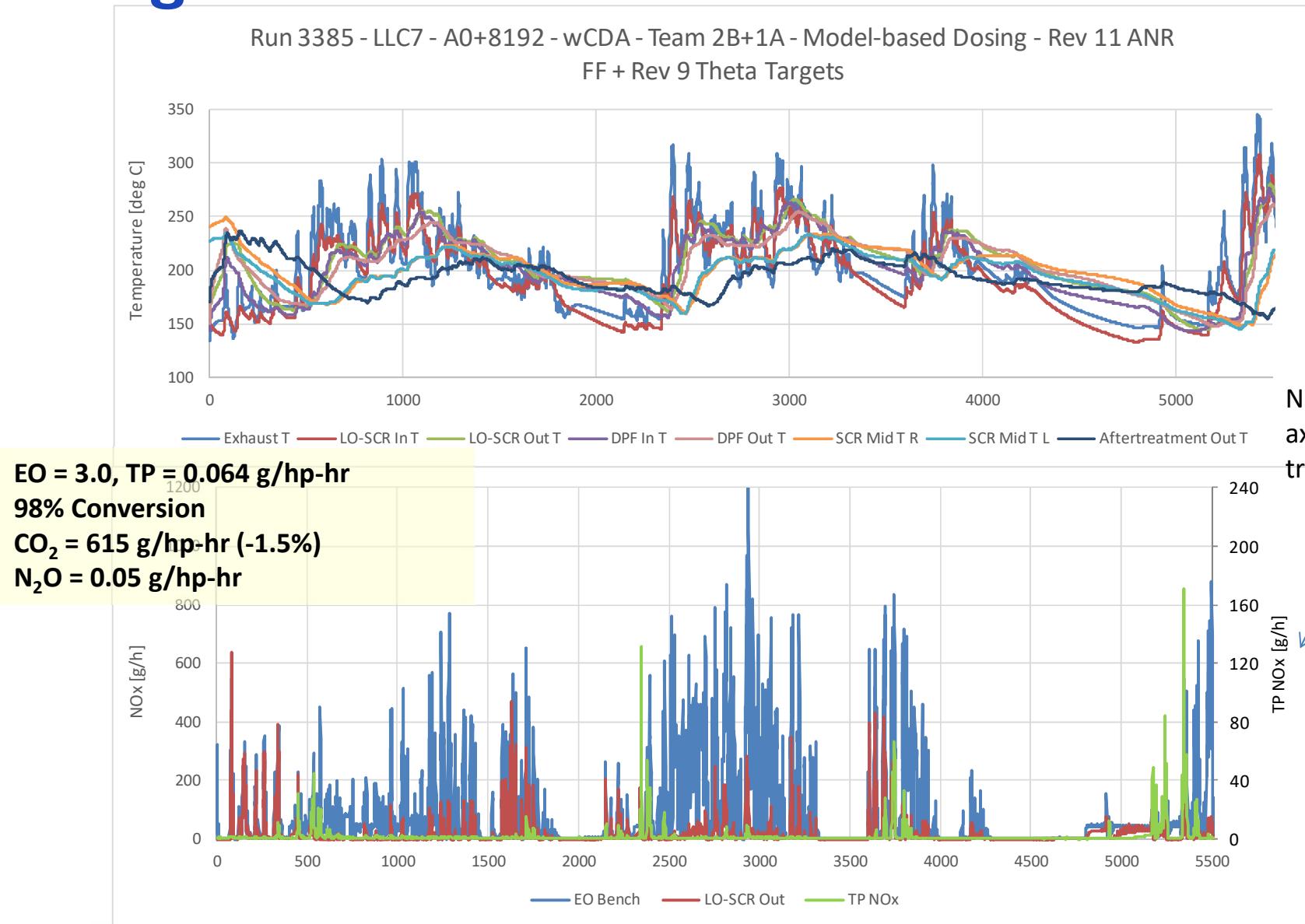
99.6% Conversion

CO₂ = 452 g/hp-hr (-0.4%)

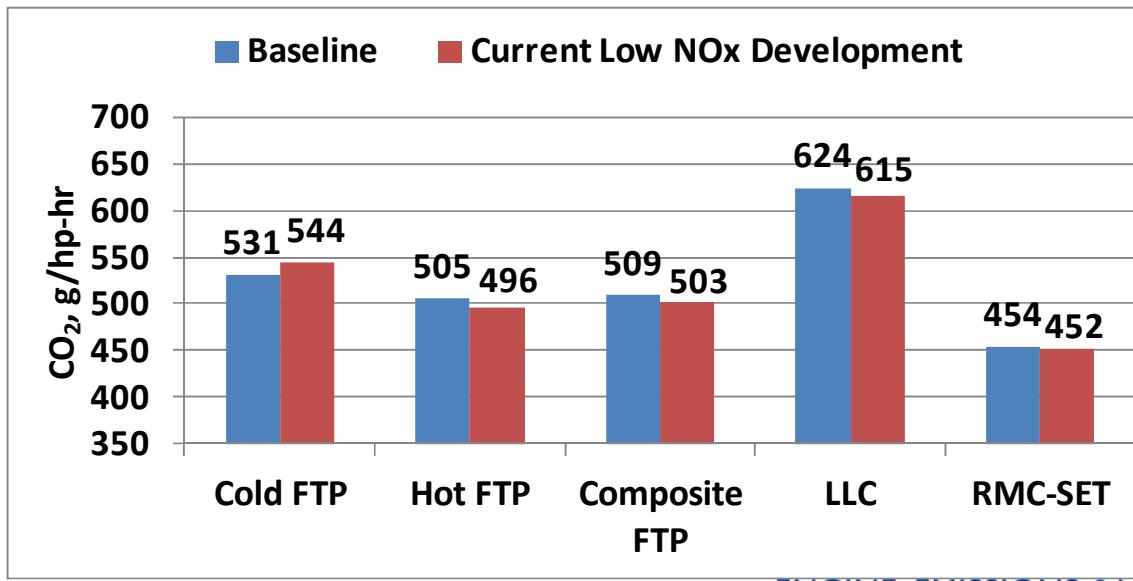
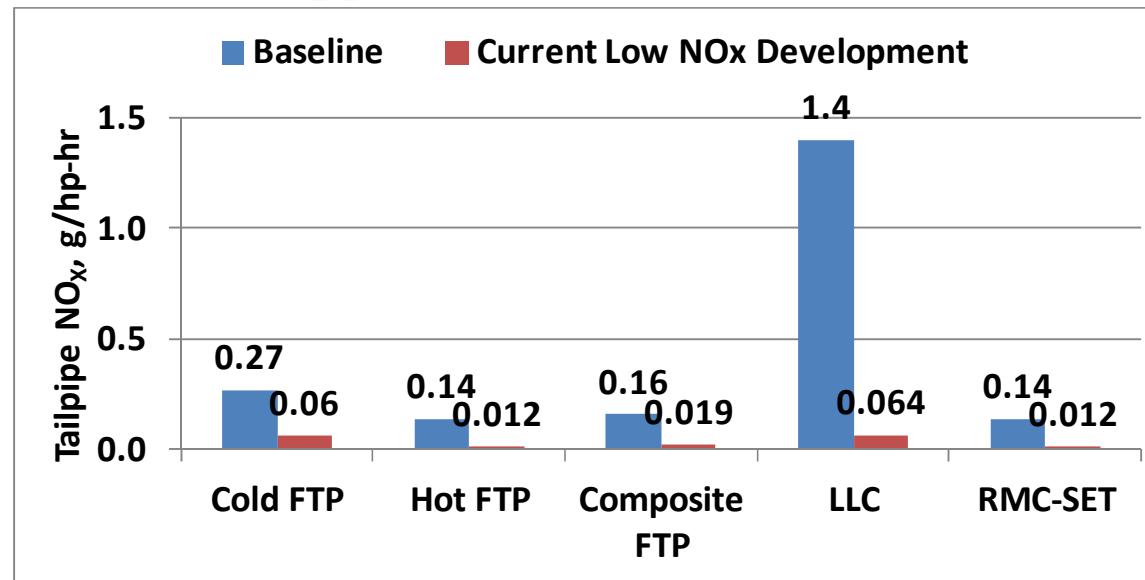
N₂O = 0.05 g/hp-hr



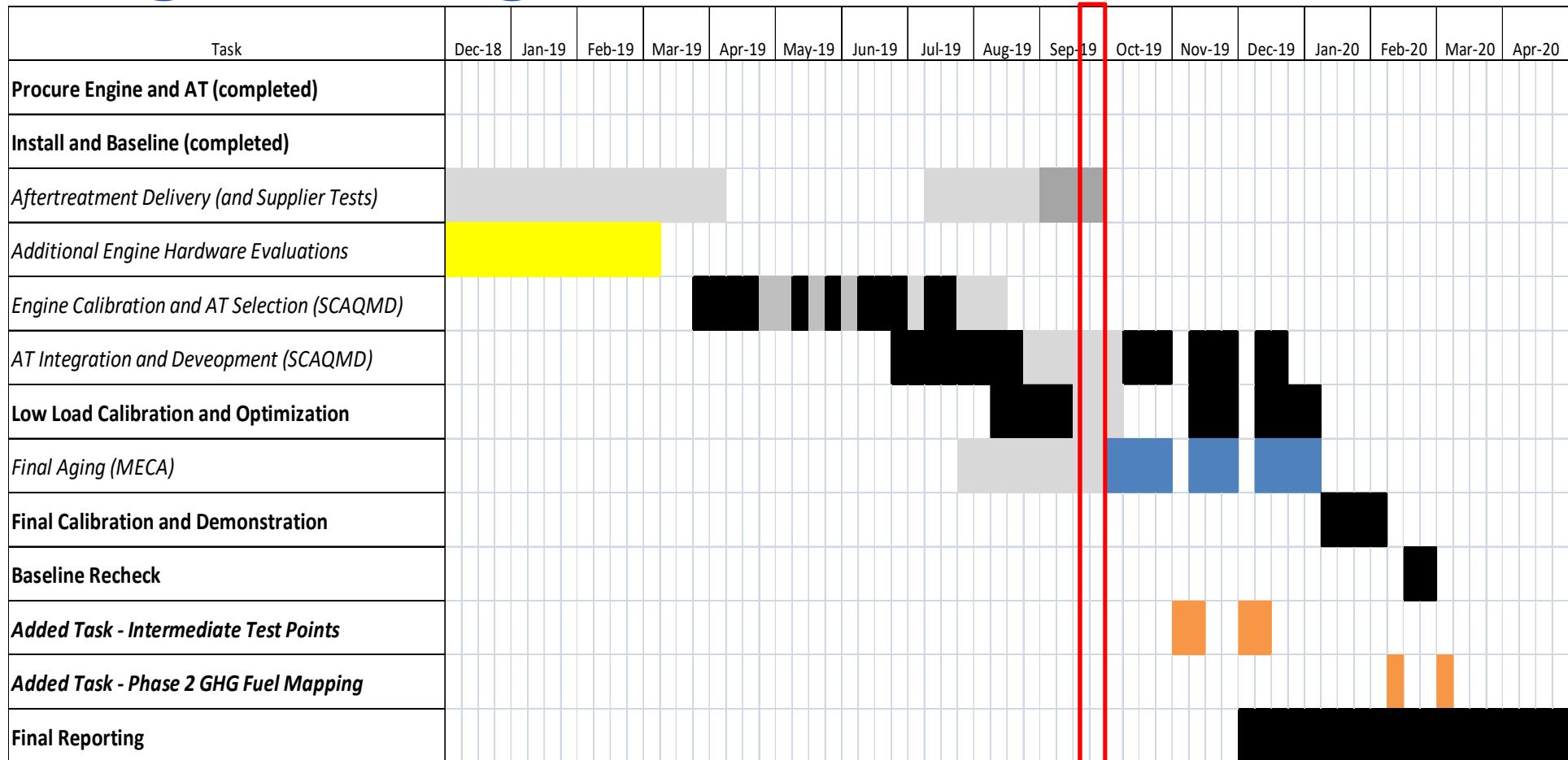
Stage 3 - LLC Performance – 2B+1A



Stage 3 Low NO_x – Current Development Status



Stage 3 - Program Timeline and Schedule



- Full Technical Program Completion February 2020
- Results on Final Aged parts Jan-Feb 2020
- Draft Report March 2020



Acknowledgments

- California Air Resources Board (CARB)
- South Coast Air Quality Management District (SCAQMD)
- U.S. EPA
- Manufacturer's of Emission Controls Association (MECA)
- SwRI CHEDEVII Consortium
- OEM Partners
 - Volvo (Stage I / Ib / 2)
 - Cummins (Stage 3)
- Program Advisory Group stakeholders
- National Renewable Energy Lab (NREL)
- All of the MECA supplier member companies who supplied hardware and engineering support

Appendix – Backup Materials

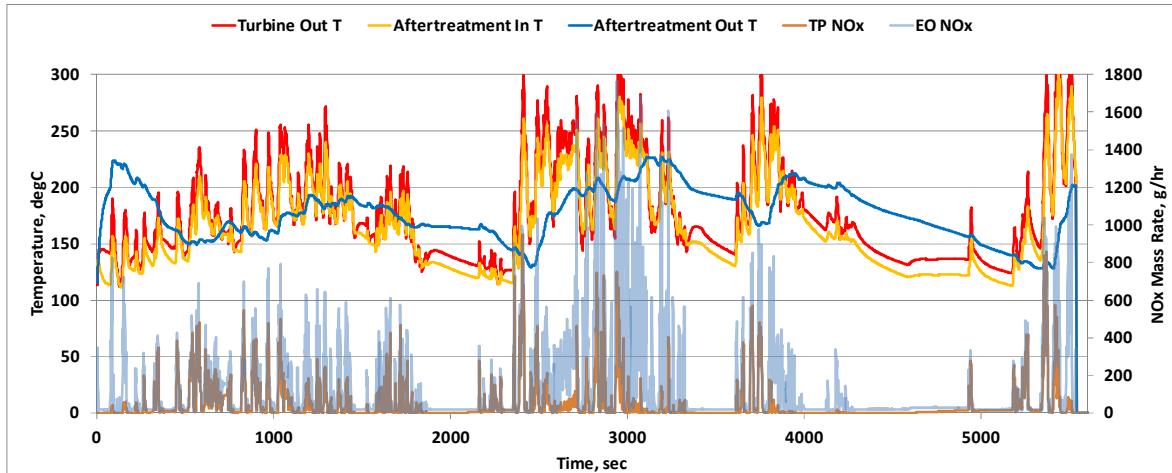


Stage Ib Final Conclusions

- Generally observed degradation in Stage Ib was smaller than for Stage I
 - FTP: **Stage Ib = 0.023 g/hp-hr** versus Stage I = 0.034 g/hp-hr
 - RMC-SET : **Stage Ib = 0.032 g/hp-hr** versus Stage I = 0.038 g/hp-hr
 - pre-ash cleaned was at 0.042 g/hp-hr
 - Canning failure and subsequent issues did have a significant impact on system performance (normal versus abnormal degradation identified)
 - Note: +0.004 Upward Adjustment Factor (UAF) should be added to both results to account for emissions due to infrequent regeneration
- RMC-SET performance was heavily influenced by ash cleaning
 - reduced temperature and backpressure post ash cleaning
 - evidence of precious metal contamination on SCRF – appears to be removable but better cleaning procedure needs to be adopted

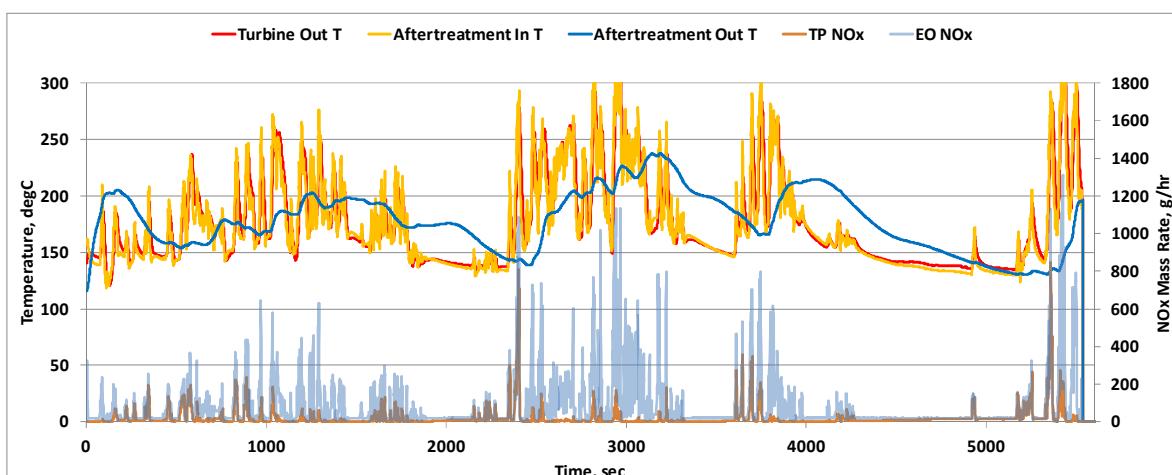
	BSCO2, g/hp-hr			
	Cold	Hot	Composite	RMC
Baseline Engine	574.2	542.6	547.4	457.7
Final ULN Config	604.4	548.8	558.2	463.6
% change	5.3%	1.1%	2.0%	1.3%
Mini-burner air	0.4%	0.2%	0.2%	
Increased SCRF Regeneration			0.3%	0.3%
Total FTP CO2 Impact			2.5%	1.6%

Stage2 - Final Low Load Cycle on Current Production Engines



Engine A - 2017

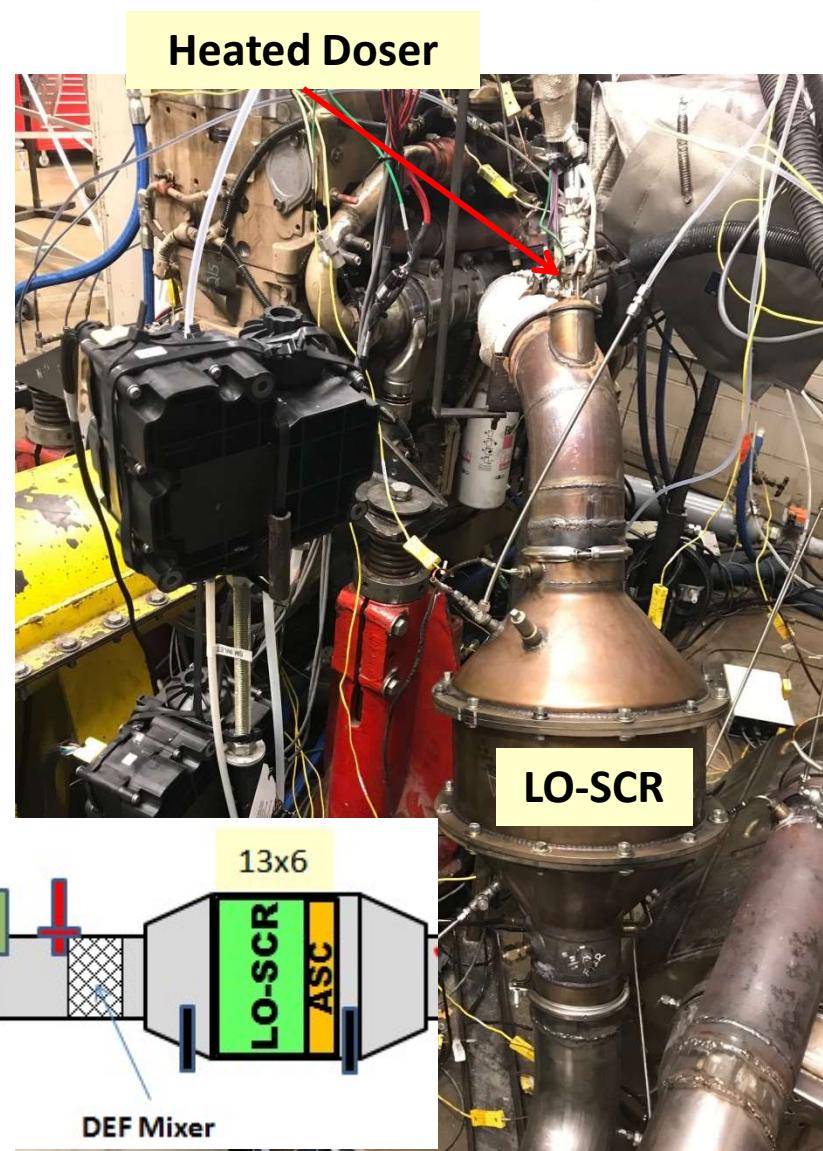
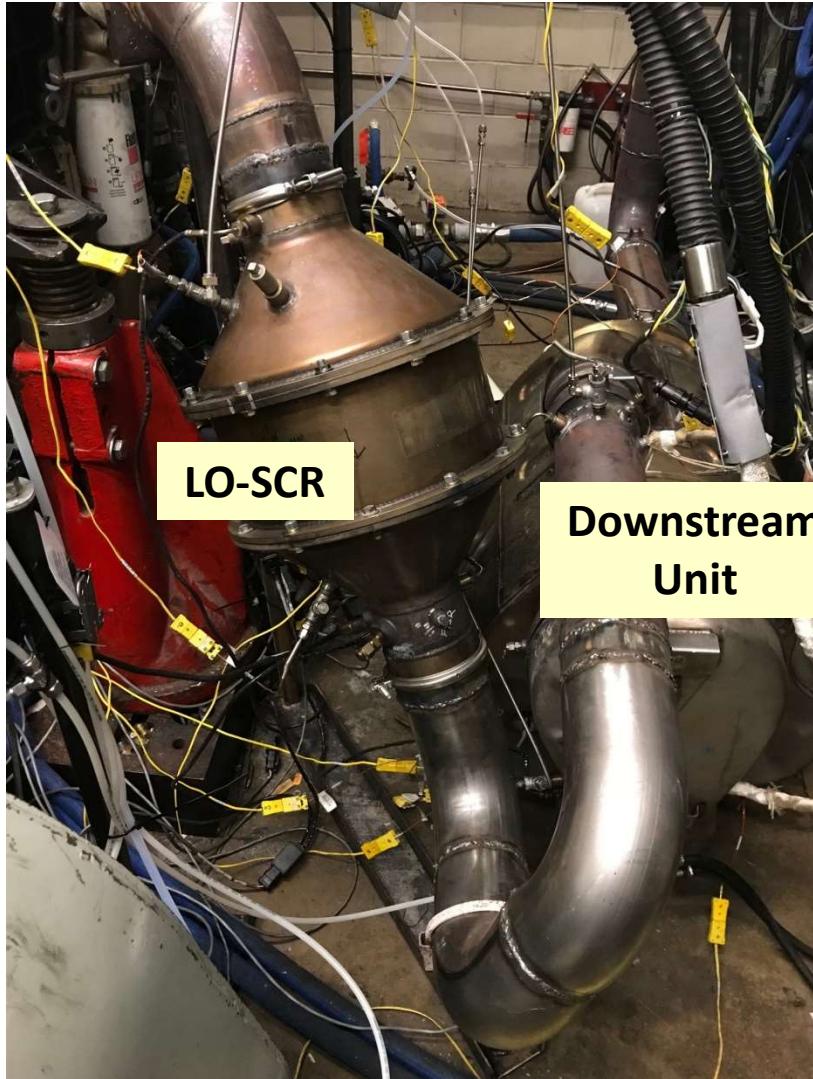
- Overall 64% conversion
- $\text{EO NO}_x = 4.2 \text{ g/hp-hr}$
- $\text{TP NO}_x = 1.5 \text{ g/hp-hr}$
- $\text{CO}_2 = 613 \text{ g/hp-hr}$



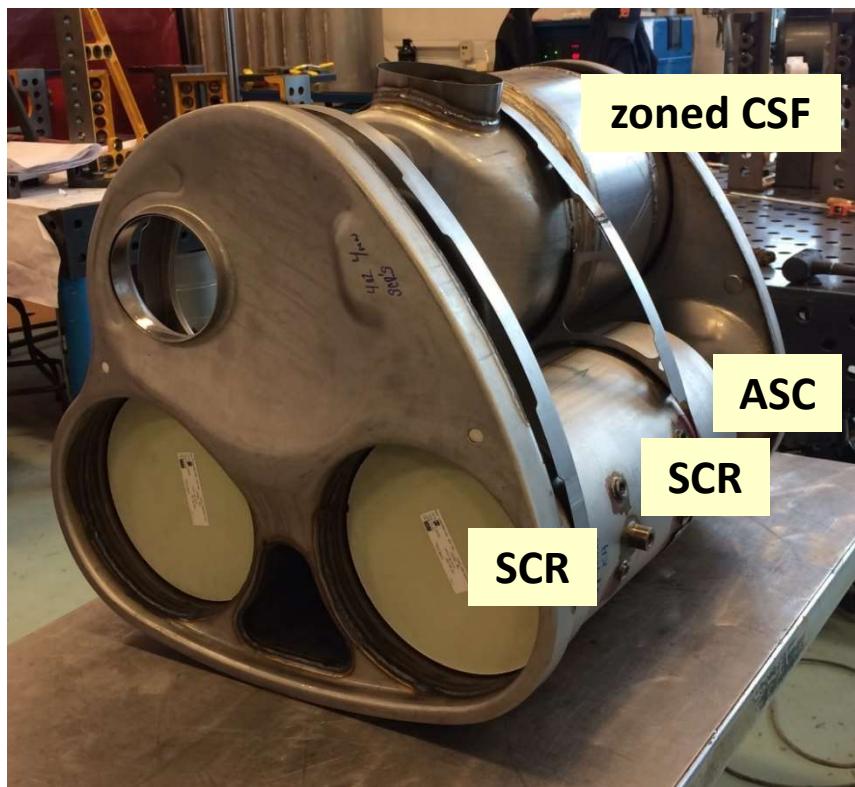
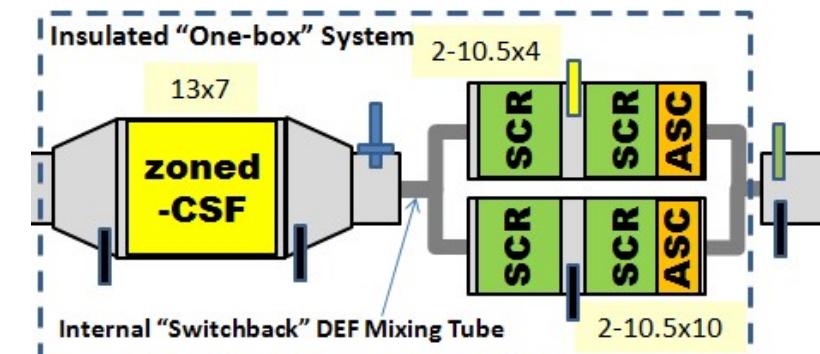
Engine B - 2018

- Overall 74% conversion
- $\text{EO NO}_x = 3.2 \text{ g/hp-hr}$
- $\text{TP NO}_x = 0.8 \text{ g/hp-hr}$
- $\text{CO}_2 = 710 \text{ g/hp-hr}$

Stage 3 Final Configuration – Overall and Upstream

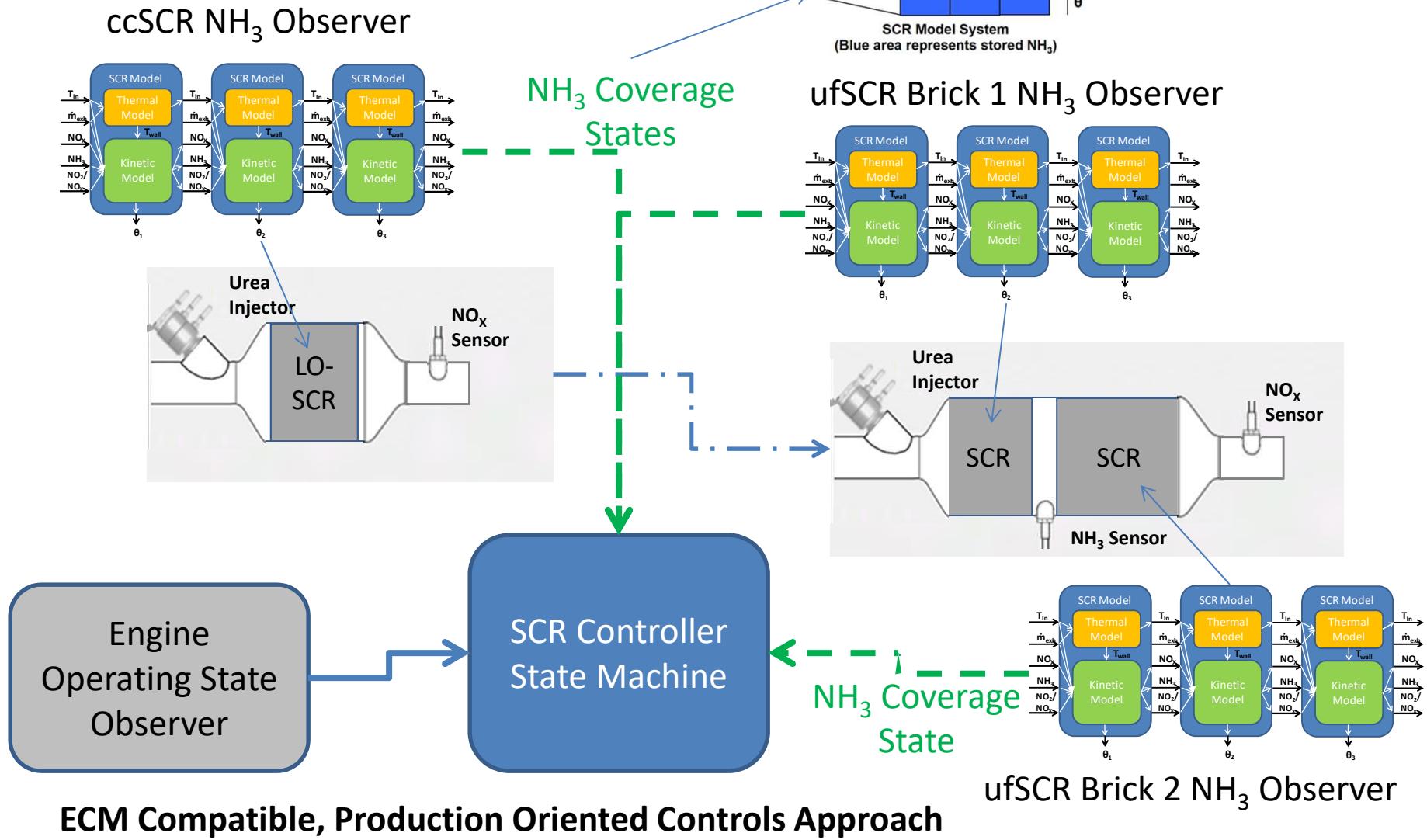


Stage 3 - Final Configuration - Downstream Package

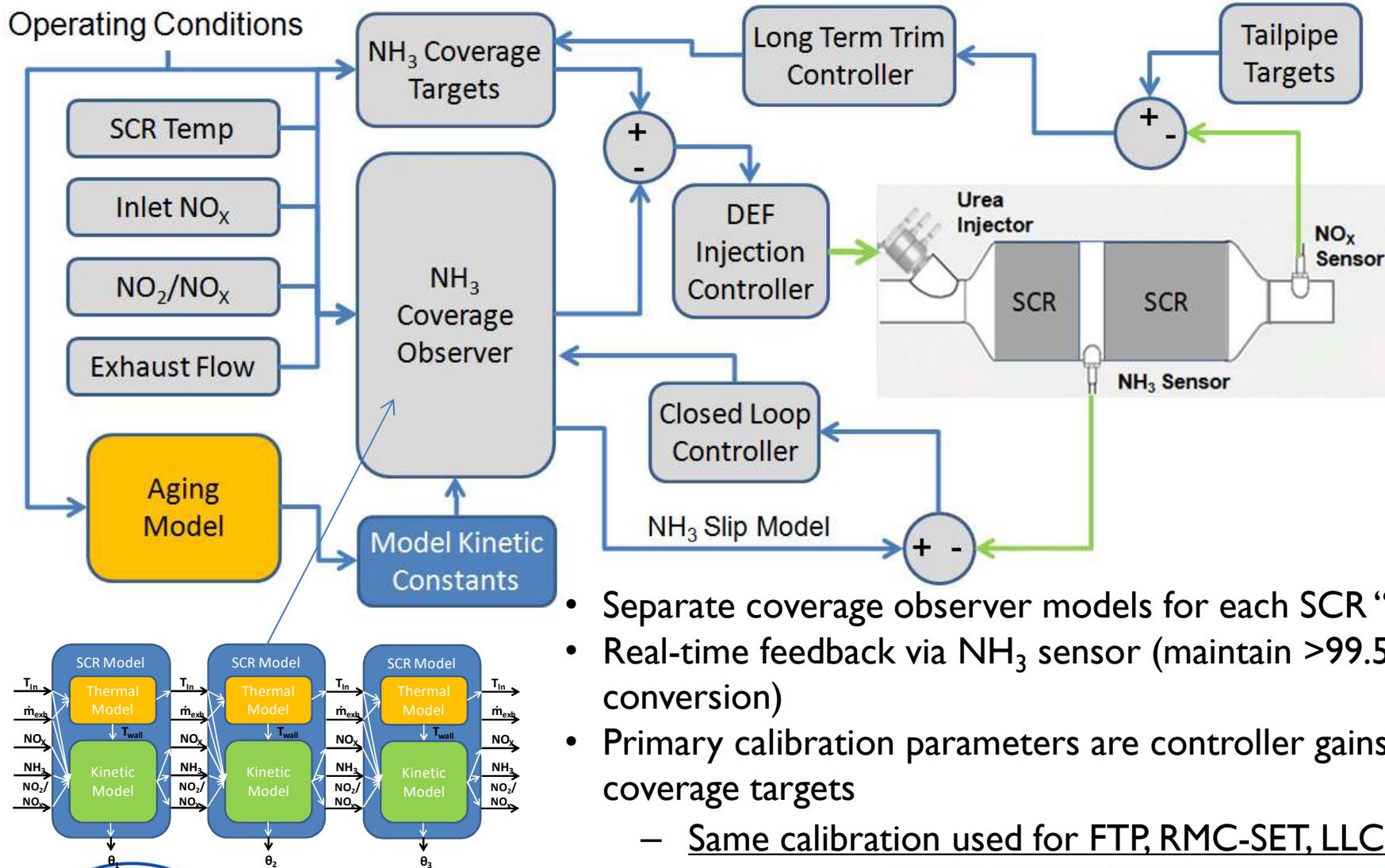


Stage 3 - Overall SCR Controller Schematic

Dual SCR / Dual Dosing

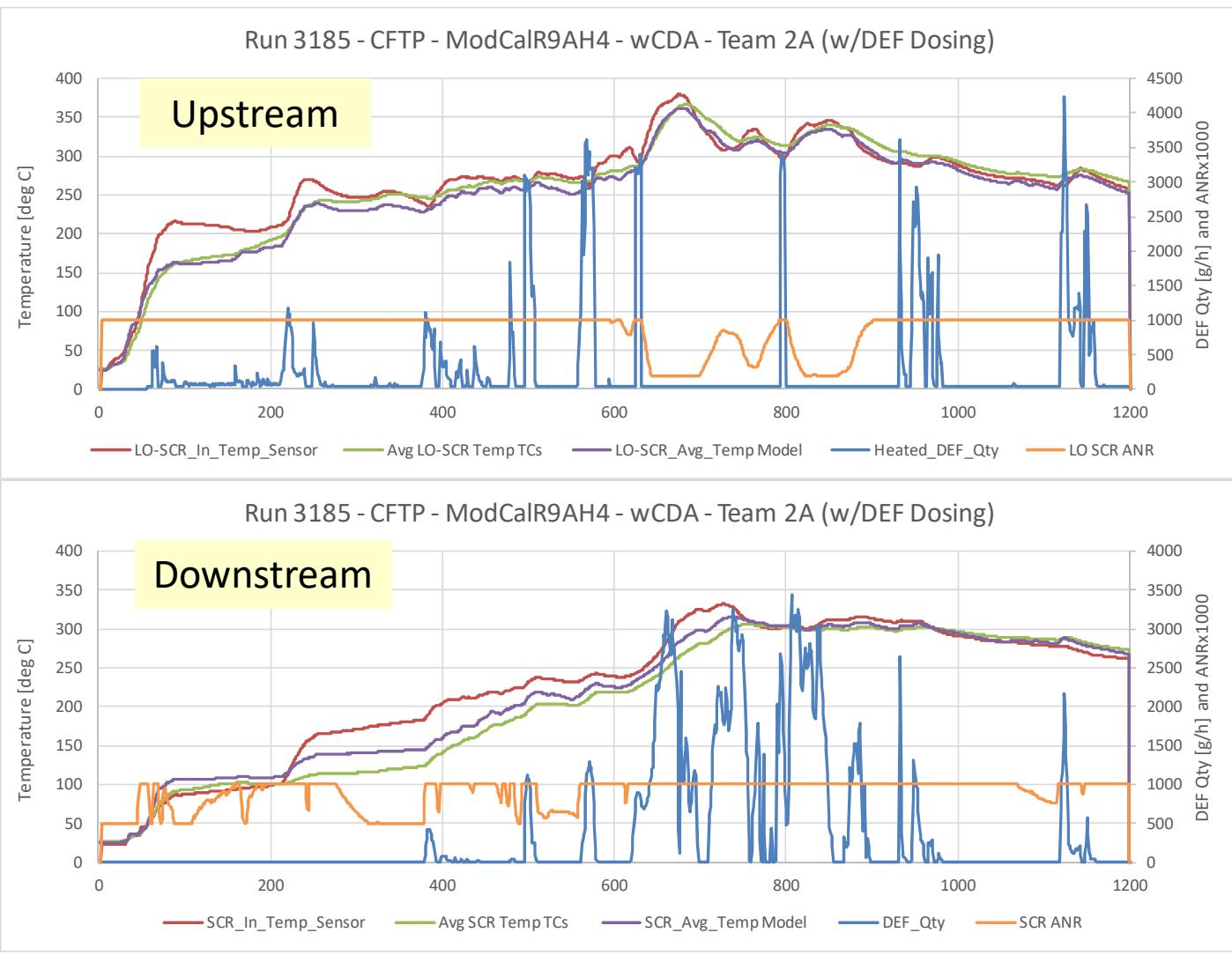


Stage 3 - Control Structure Example for Downstream Catalyst / Doser (ufSCR)



- Separate coverage observer models for each SCR “brick”
- Real-time feedback via NH₃ sensor (maintain >99.5% conversion)
- Primary calibration parameters are controller gains and coverage targets
 - Same calibration used for FTP, RMC-SET, LLC, etc.

Stage 3 - Dual Dosing Approach – Cold FTP Example



- Upstream (heated) dosing dominates early dosing
- Both system active in transition
- Downstream dosing dominates high temperature with AT warm
- Upstream dosing comes back into play as system cools to prepare storage